Juno Constraints on the Formation of Jupiter's Magnetospheric Cushion Region

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Abstract: Observations by the Pioneer, Voyager, Ulysses, and Galileo spacecraft in Jupiter's dayside magnetosphere revealed a cushion region, where the magnetic field became increasingly dipolar and the 10-hr periodicity associated with rotation of the magnetodisc was no longer visible. Focused observations at the dawn terminator by the Juno spacecraft provide critical constraints on the formation physics of the dayside cushion. We observe a persistent 10-hr periodicity at dawn with only minor distortions of the field near the magnetopause boundary, indicating the absence of a systematic dawn cushion region. These data suggest that the dayside cushion is not formed via mass loss associated with magnetic reconnection along a localized X line but rather may be due to the gradual compression of the dawnside magnetic field as it rotates toward local noon.

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Key Points:

- Jupiter's magnetosphere was likely in a compressed state during the first several Juno perijove passes
- Jupiter's magnetodisc extends to the magnetopause along the dawn terminator, indicating the absence of a thick dawn *cushion* region
- The dayside cushion likely forms as a result of the gradual dipolarization of magnetodisc field lines

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Juno Constraints on the Formation of Jupiter's Magnetospheric Cushion Region

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Abstract Observations by the Pioneer, Voyager, Ulysses, and Galileo spacecraft in Jupiter's dayside magnetosphere revealed a *cushion* region, where the magnetic field became increasingly dipolar and the 10-hr periodicity associated with rotation of the magnetodisc was no longer visible. Focused observations at the dawn terminator by the Juno spacecraft provide critical constraints on the formation physics of the dayside cushion. We observe a persistent 10-hr periodicity at dawn with only minor distortions of the field near the magnetopause boundary, indicating the absence of a systematic dawn cushion region. These data suggest that the dayside cushion is not formed via mass loss associated with magnetic reconnection along a localized X line but rather may be due to the gradual compression of the dawnside magnetic field as it rotates toward local noon.

Plain Language Summary Jupiter's space environment is strongly influenced by its fast rotation period of ~10 hr. Dipolar magnetic field lines are stretched out by centrifugal forces out to distances up to 100 times Jupiter's radius. Observations of Jupiter's dayside magnetosphere from several spacecraft revealed a *cushion* region that was thought to contain an absence of plasma, constraining how mass and magnetic field are circulated around the planet. This cushion was thought to extend to dawn local times, but there have been very few spacecraft observations of this region until Juno. The Juno data presented here demonstrates that no systematic cushion region exists near the dawn terminator such that flux circulation models need to be reassessed in order to account for a cushion region that is confined closer towards noon local times.

1. Introduction

Jupiter's massive, rotationally driven magnetosphere generates physical processes not present at other planetary bodies. In particular, the so-called cushion region found in the outer magnetosphere is specific to Jupiter (Went et al., 2011). This region was first identified in Pioneer 10 magnetic field observations, where the stretched magnetodisc fields found closer to the planet transitioned to a more turbulent, dipolar configuration with increasing distance from Jupiter (Smith et al., 1974, 1976). The ~10-hr periodicity associated with Jupiter's rotation was no longer visible. Observations of the cushion region in the morning sector of Jupiter's outer magnetosphere have since been confirmed with the Voyager, Pioneer 11, Galileo, and Ulysses spacecraft (Balogh et al., 1992; Kivelson et al., 1997; Kivelson & Southwood, 2005; Ness et al., 1979a, 1979b; Smith et al., 1975, 1976; Went et al., 2011). An additional characteristic of the cushion was magnetic nulls that indicated the presence of highly localized increases in plasma content (Haynes et al., 1994; Leamon et al., 1995).

The cushion was first incorporated into a schematic of Jupiter's magnetic flux circulation by Vasyliunas (1983). This region was attributed to flux tubes that were depleted of mass from magnetic reconnection in Jupiter's magnetotail and would rotate from dawn to dusk, eventually reassimilating into the dusk plasma sheet. This concept of the cushion was refined by Kivelson and Southwood (2005), who further argued the observed magnetic nulls arose from instabilities forming at the outer edge of the plasma sheet in the inner magnetosphere. Khurana et al. (2004) illustrated the cushion region as confined to dayside local times (~0800–1600 hr), where it served to buffer the magnetodisc from compressions of the subsolar magnetopause.

More recently, Delamere and Bagenal (2010) suggested that the cushion region was related to the viscous interaction between magnetospheric and magnetosheath plasmas along Jupiter's dawn flank. Instead of consisting of depleted flux tubes, they asserted that the cushion acted as a dawnside boundary layer with a thickness of ~10 R_J. Finally, Delamere et al. (2015) considered the cushion region as the accumulation of expelled magnetic flux from the current sheet via reconnection, sandwiched between the magnetodisc in the inner magnetosphere and magnetopause.

Many of the discussed concepts of the cushion region require its systematic presence at dawn local times. However, direct observations of a thick (i.e., $>> 1$ R_J) cushion at Jupiter have been limited to the morning sector (i.e., postdawn). The dawn terminator of Jupiter's outer magnetosphere has been largely unexplored by previous missions (Went et al., 2011). Fortunately, the first several orbits of the Juno spacecraft (Bolton, 2010; Bolton et al., 2017) around Jupiter resulted in dwell times of weeks in Jupiter's dawnside magnetosphere (Bolton et al., 2017). This orbital configuration enabled unprecedented study of the dawn terminator and the unambiguous evaluation of its role in the formation of the cushion region.

Here we use Juno data collected in Jupiter's outer magnetosphere to demonstrate the systematic absence of a significant cushion region at dawn. We find that the 10-hr periodicity associated with magnetodisc rotation about Jupiter persists out to the magnetopause, with modest distortions limited to within a day before a magnetopause crossing. We further show that plasma densities previously reported in the cushion region are consistent with those observed in the dawnside plasma sheet. We suggest that the cushion does not consist of disconnected flux tubes but rather forms postdawn due to the gradual dipolarization of Jupiter's magnetic field as it is compressed by the subsolar magnetopause.

2. Data Analysis

We utilized data collected by the Juno spacecraft between July 2016 and January 2017. This time period spanned Juno's first four 53-day orbits around Jupiter. The local time of the spacecraft in the outer magnetosphere was almost exactly at dawn (i.e., 0600 hr), with dwell times of several weeks at large (i.e., $R > 75$ R_J) Joviocentric distances. Juno's near equatorial latitude enabled observation of the oscillatory magnetodisc motion generated by the 10° angular offset of Jupiter's magnetic field from its rotation axis. This orbital configuration differed from previous spacecraft's transits along Jupiter's dawn terminator that were limited to only a few days in the outer magnetosphere (Bagenal et al., 2017), enabling a more comprehensive analysis of this region.

Data from the Magnetometer Investigation (MAG; Connerney et al., 2017) and Waves Investigation (Kurth et al., 2017) on Juno were used to characterize Jupiter's outer magnetosphere. Particle measurements from the Jovian Auroral Distributions Experiment (McComas et al., 2013) were not regularly available during this time period. Three-dimensional magnetic field vector measurements were transformed from sensor coordinates into the Jupiter-De-Spun-Sun (JSS) nonrotating frame, where the Z axis lies along the direction of Jupiter's spin axis, the Y axis lies along the direction of the cross product between the Z axis and the unit vector of Jupiter to the Sun, and the X axis completes the right-handed coordinate system (i.e., the Jupiter-Sun-Equatorial (JSE) frame in Bagenal et al., 2017, or the JUNO_JSS frame in Juno SPICE kernels). Corresponding spherical polar coordinates, (B_R, B_θ, and B_Φ), were calculated as $B_R = \mathbf{B}\cdot[\cos(\Phi_{sc})\ \sin(\theta_{sc}),\ \sin(\Phi_{sc})\ \sin(\theta_{sc}),\ \cos(\theta_{sc})]$, $B_\theta = \mathbf{B}\cdot[\cos(\Phi_{sc})\ \cos(\theta_{sc}),\ \sin(\Phi_{sc})\ \cos(\theta_{sc}),\ -\sin(\theta_{sc})]$, and $B_\Phi = \mathbf{B}\cdot[-\sin(\Phi_{sc}),\ \cos(\Phi_{sc}),0]$, where θ_{sc} and Φ_{sc} were the polar (i.e., from the Z axis) and azimuthal (i.e., in the XY plane) angles of the Juno spacecraft in JSS coordinates, respectively. Vectors were averaged to one sample per minute.

Plasma wave electric field spectra were provided by Waves for 50 Hz to 41 MHz at a cadence of 10 s. The lower frequency cutoff of continuum emission in the magnetosphere was used in conjunction with the magnetic field magnitude to provide estimates of the total electron density. In addition, the presence of this emission was evaluated along with rotations of the vector magnetic field to identify spacecraft transits of Jupiter's magnetopause. This approach has been successfully used (e.g., Gershman et al., 2017; Hospodarsky et al., 2017; Kurth et al., 2002) to identify magnetopause boundaries. A sharp disappearance of continuum radiation accompanied by a change in one or more components in the magnetic field vector indicates that the spacecraft has moved from the closed-field magnetosphere into the *open* magnetosheath.

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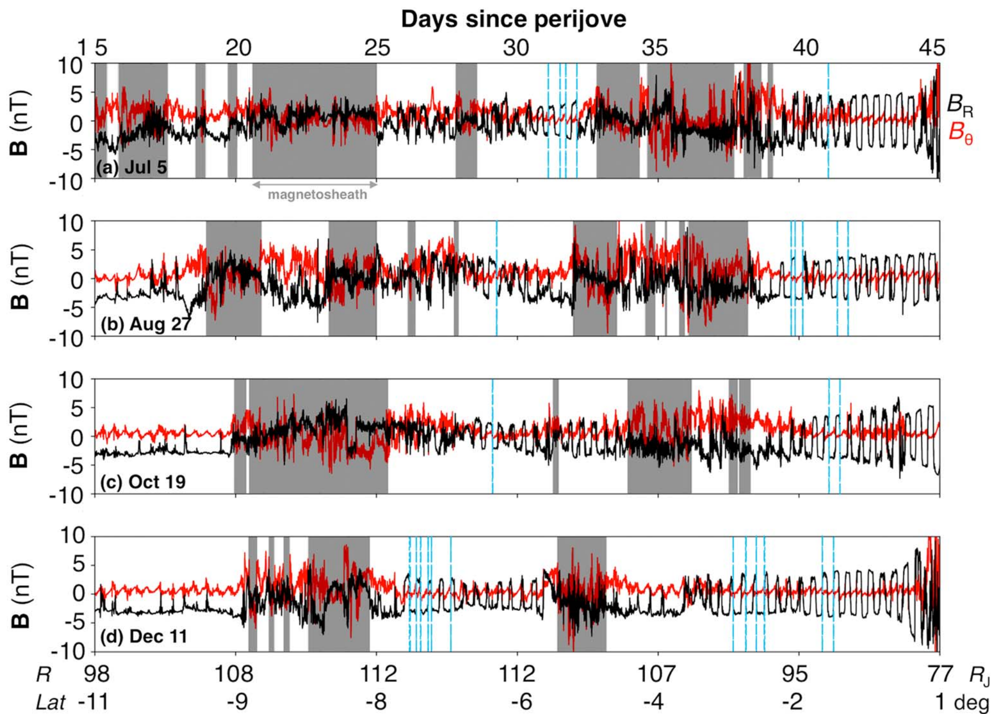

Figure 1. Radial (black) and polar (red) components of Juno/MAG magnetic field vectors in the outer magnetosphere for the first four Juno orbits around Jupiter (i.e., July 2016 through January 2017). Data are organized as days since perijove, that is, closest approach of the spacecraft to the planet. The local time of all observations was dawn (i.e., 0600 hr). Shaded regions indicate that the spacecraft was outside the magnetosphere as determined by MAG and Waves. Vertical blue dashed lines correspond to pristine (as described in the text) current sheet crossings at large radial distances that are analyzed in section 2.2. No systematic dawn cushion is visible in these data, as sustained distortions of the magnetic field are limited to the gray-shaded regions outside of Jupiter's magnetosphere.

2.1. Data Overview

An overview of the B_R and B_θ components of Jupiter's magnetic field along the dawn terminator is shown in Figure 1 for the first four Juno orbits. The 10-hr periodicity associated with the planetary rotation period in B_R endured throughout the outer magnetosphere. Given that the average magnetopause standoff distance along Jupiter's dawn flank is on the order of ~100 R_J (see Figure 1, Joy et al., 2002, and Hospodarsky et al., 2017), the uninterrupted 10-hr periodicity observed for distances $R \leq 100$ R_J suggested that no systematic 10 R_J-thick layer (e.g., Delamere & Bagenal, 2010) existed between the magnetodisc and magnetopause. The field magnitude remained at ~5 nT in this region, with some sporadic enhancements associated with magnetopause compressions (Gershman et al., 2017).

The magnetodisc fields became distorted only in regions immediately adjacent to the magnetopause. The extent of these distortions is further quantified in Figure 2, where the direction of the magnetic field was histogrammed as a function of time from its nearest magnetopause crossing (i.e., closest edge of a shaded region in Figure 1). The average direction of **B** far from the magnetopause was consistent with the expected bend back of the magnetic field due to subcorotating plasmas in the outer magnetosphere (Khurana et al., 2004). Regions of more dipolar field were highly limited in extent to within less than a day of the nearest crossing. Due to the strong localization of these regions to immediately adjacent to the magnetopause, it is likely that their spatial extent is $\lesssim$1 R_J, consistent with magnetopause boundary layers as described by Gershman et al. (2017).

2.2. Current Sheet Structure

The structure of current sheets was analyzed for 26 magnetodisc crossings with distances $R > 90$ R_J, indicated with vertical dashed lines in Figure 1. Minimum variance analysis (Sonnerup & Cahill Jr., 1967) was performed on the magnetic field data spanning 1 hr before and after the time of each crossing, defined here as the

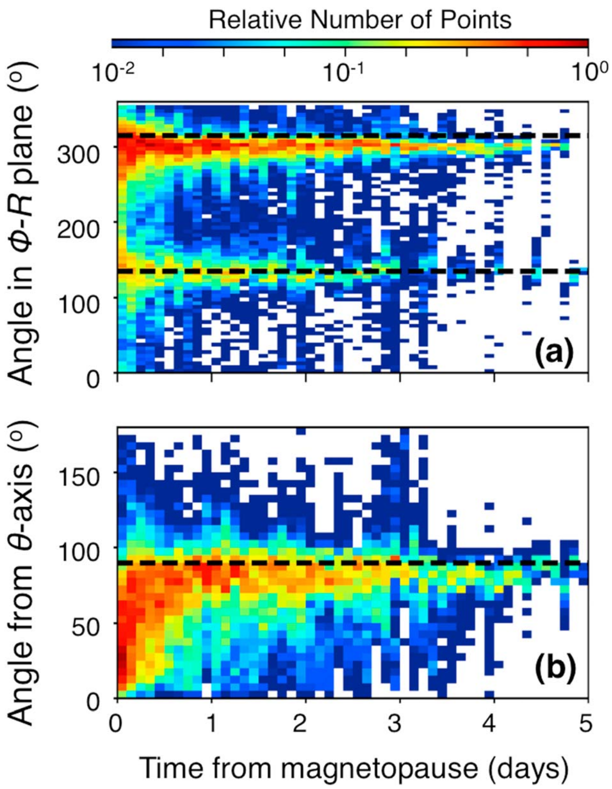

Figure 2. Histograms of the angles of the magnetic field vector (a) in the R-Φ plane (0° and 90° correspond to along the R and Φ axes, respectively) and (b) from the θ axis are shown as a function of time from the nearest magnetopause crossing (i.e., nearest edge of a shaded region in Figure 1). The two dominant azimuthal angles arise due to the equal and opposite fields on either side of the magnetodisc current sheet.

minimum in magnetic field magnitude. The duration of each crossing, defined as the full width at $1/\sqrt{2}$ of the maximum value of the largest varying component, was determined. Example magnetodisc crossings are shown in Figure 3a for thinner, ~2-min (black), and thicker, ~40-min (red), current sheets. Although many other current sheets are visible in Figure 1, they exhibited significant variation near the crossing such that a thickness was not readily recovered. The pristine 26 crossings used here showed monotonic variation for the duration of the crossing. A histogram of current sheet thicknesses is provided in Figure 3b, which shows a mean duration of 21 ± 10 min. If we assume that Jupiter's current sheet undergoes a sinusoidal variation with amplitude ~10° in 10 hr, the maximum angular speed of the current sheet at R ~ 100 R_J is ~200 km/s. Therefore, the half thicknesses of the dawnside current sheet in the outer magnetosphere range from ~1 to 3 R_J. These dimensions are consistent with the ~2 R_J average half thickness at dawn reported by Connerney et al. (1981) and Khurana et al. (2004), though it is likely that the magnetodisc thickens somewhat closer to the planet.

2.3. Dayside-Dawn Comparison

Finally, a comparison between the outer magnetosphere in the dayside cushion (~1300 hr) and near the dawn terminator (~0600 hr) are shown in Figure 4, observed by Galileo and Juno, respectively. The dayside cushion region interval shown in Figure 4a is identical to that presented by Kivelson and Southwood (2005). The magnetic field and plasma wave spectra are shown for each interval. On the dayside, the magnetodisc signature broke down at R ~ 30 R_J. The current sheet in the inner magnetosphere was thicker than at dawn, with variations in B_R appearing nearly sinusoidal. Beyond 30 R_J, the Galileo magnetometer (Kivelson et al., 1992) showed that the field became dipolar and dominated with compressive fluctuations. The cushion persisted out to ~60 R_J, after which Galileo crossed the magnetopause. The electron density in the cushion region inferred from the plasma wave spectra (Gurnett et al., 1992) was ~0.01 cm^{-3}. At dawn (Juno observations, Figure 4b), no such cushion region was observed, with thin magnetodisc current sheet crossings observed all the way to the magnetopause at ~110 R_J. Electron densities in the center of the plasma sheet were also

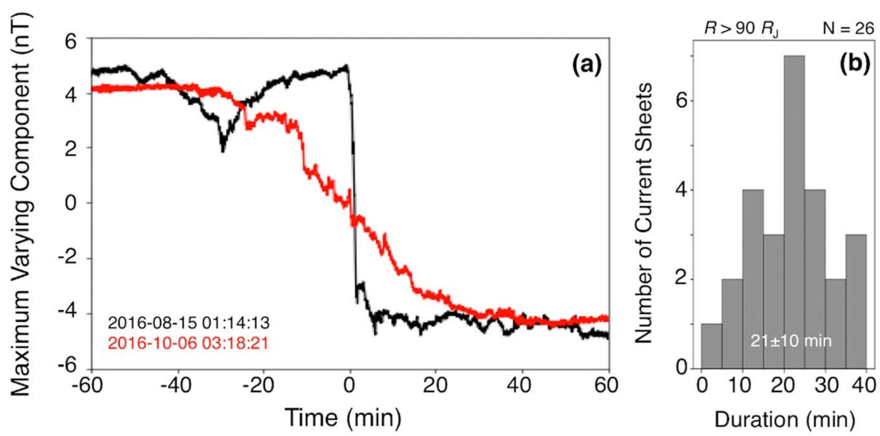

Figure 3. (a) Example current sheet crossings of the magnetodisc in the outer magnetosphere. The maximum varying component of the field for a shorter (black, 2-min duration, unit vector [−0.75,−0.66,0.04] in R-θ-Φ) and longer (red, 40-min duration, unit vector [−0.54,−0.84,0.11] in R-θ-Φ) crossing are shown. (b) A histogram of the durations of 26 clear current sheet crossing signatures in the outer magnetosphere indicated with vertical blue dashed lines in Figure 1.

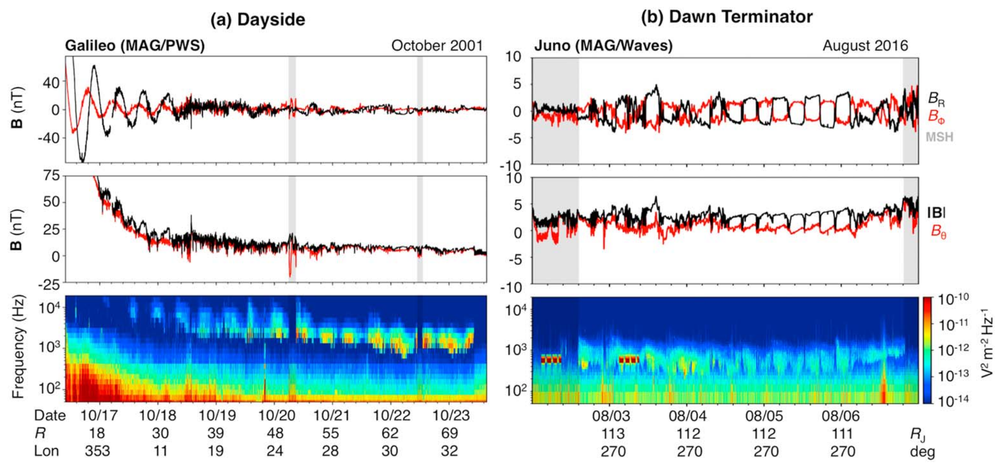

Figure 4. (a) The dayside cushion region (local time ~ 1300 hr) as reported by Kivelson and Southwood (2005) using Galileo data and (b) the dawn terminator with no cushion (local time ~ 0600 hr) as observed by Juno. Magnetic field and plasma wave spectra are shown for both intervals. MAG = Magnetometer Investigation; MSH = Magnetosheath; PWS = Plasma Wave Subsystem.

~0.01 cm^{-3}, with modest increases close to the magnetopause associated with the magnetopause boundary layer (Ebert et al., 2017; Gershman et al., 2017).

3. Discussion

Juno's nominal 53-day orbit is approximately twice that of a solar rotation (i.e., 27 days). Therefore, variations in Jupiter's magnetosphere associated with regular solar forcing (e.g., high-speed solar wind streams [McComas et al., 2014]) are synchronized with Juno's orbital period. Such repetitions were present in Figure 1 where crossings of the magnetopause (i.e., increases in solar wind dynamic pressure) occurred every ~12–14 days. Corresponding observations of the solar wind speed from the Solar Wind Electron Proton Alpha Monitor instrument (McComas et al., 1998) on the Advanced Composition Explorer spacecraft (Stone et al., 1998) at 1 AU over late 2016 (not shown) indicated high-speed streams occurring with a similar cadence. Given this pattern, and the magnetosheath observed near 10, 23, 35, and 45 days since perijove in Figure 1, Jupiter's magnetosphere should have been in a compressed state during Juno's first several perijove passes. Such a configuration may have impacted the mapping of auroral features to regions of Jupiter's magnetosphere (Vogt et al., 2011). A synoptic view of Juno magnetometer data enabled the recovery of this pattern despite the absence of an upstream monitor.

In the inner magnetosphere, centrifugal forces driven by Jupiter's rotation result in a stretched field configuration, that is, a magnetodisc, at all local times (Goertz, 1979). These forces are balanced by the $\mathbf{J} \times \mathbf{B}$ current system, enabling a corotating plasma sheet (Hill, 1979; Vasyliunas, 1983). However, beyond a critical radius ($<30\ R_J$ at Jupiter) the $\mathbf{J} \times \mathbf{B}$ forces are no longer able to provide this balance (Bagenal et al., 2016; Dougherty et al., 2017; Hill, 1979). Therefore, simple stress balance suggests that a magnetodisc need not exist beyond this critical distance. Nevertheless, stretched fields are regularly observed in Jupiter's outer magnetosphere. The phase of magnetodisc crossings in the outer magnetosphere with respect to Jupiter's rotation have been shown to be consistent with a wave that propagates radially outward from the location of corotation breakdown (Northrop et al., 1974). The magnetic pressure adjacent to the plasma sheet enables the confinement of magnetodisc plasmas to the equator at large radial distances (Khurana et al., 2004).

Due to Jupiter's rotation, polar magnetic flux is asymmetrically swept back as it expands into the magnetotail (Khurana et al., 2004; see Figure 5d). This flux provides the confining magnetic pressure described above. On the dayside, because there is little magnetic pressure provided by the expanding polar flux, there is not sufficient force to maintain a magnetodisc in the outer magnetosphere. It follows that a cushion of more dipole-like field on the dayside between the magnetopause and magnetodisc in the inner magnetosphere would be possible. Its thickness would be determined by distance between the radius of corotational breakdown and

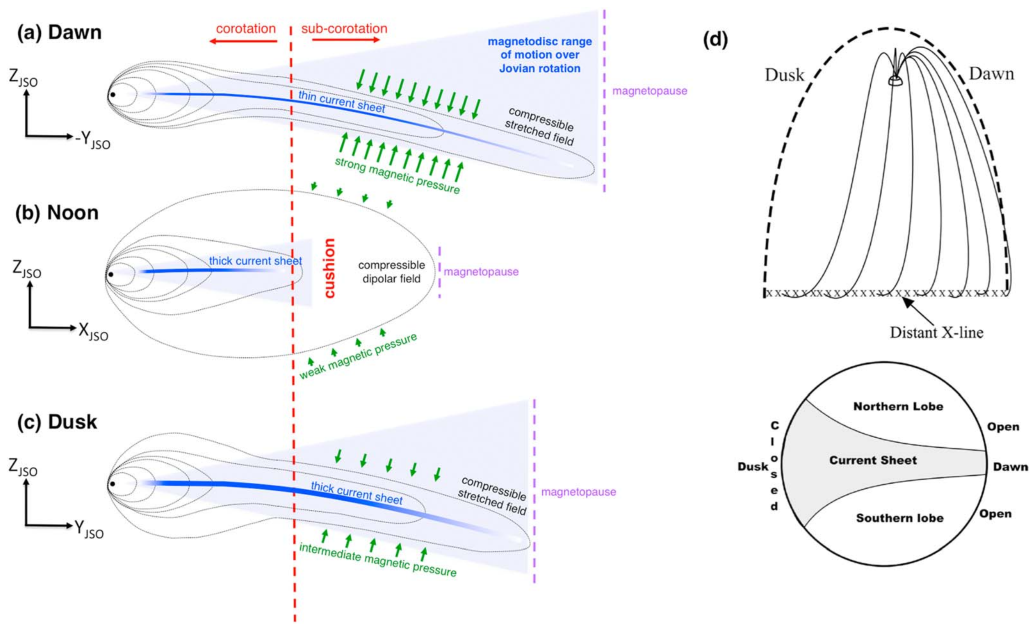

Figure 5. Side-view illustration of Jupiter's magnetodisc current sheet at (a) dawn, (b) noon, and (c) dusk. Below a critical radius (red dashed line), the magnetodisc plasma corotates with the planet at all local times. In the outer magnetosphere, the plasma subcorotates such that the observed vertical deflection of the current sheet lags that in the inner magnetosphere. (d) Polar magnetic flux (adapted from Figure 24.20 of Khurana et al., 2004) provides pressure to asymmetrically confine magnetodisc plasmas near the equator at dawn and dusk. Similar pressure is not present at noon such that as plasma rotates from dawn toward the dayside, the magnetodisc fields gradually dipolarize. Because no change in magnetic topology has occurred, plasma sheet particles remain tied to the now dipolar field lines, resulting in a *cushion* region. As the dayside field rotates toward dusk, the field reexpands and is reconfined to the equator by the polar magnetic flux.

the subsolar magnetopause standoff distance, resulting in the ~30 R_J cushion presented in Figure 4. As illustrated in Figure 5, this cushion would form as a consequence of the gradual weakening of the magnetodisc current density and quasi-adiabatic dipolarization of the field as flux tubes rotate from dawn to noon local times. Following the illustration in Figure 5d, the dayside cushion would disappear toward dusk as both the magnetopause standoff distance (Joy et al., 2002) and pressure from the polar magnetic flux increase. The increased current sheet thickness at dusk compared to that at dawn is consistent with a dawn-dusk asymmetry in both magnetopause standoff distance (Joy et al., 2002; Ogino et al., 1998) and expansion of polar magnetic flux (Khurana et al., 2004). A significant dayside cushion region would not be expected in smaller rotationally driven magnetospheres (e.g., Saturn [Went et al., 2011]), where the magnetopause standoff distance is not substantially further out from the planet than the radius at which corotation breaks down (Arridge et al., 2008).

If the dayside cushion consists of flux tubes that have rotated from dawn without any change in magnetic topology, then its plasma content must directly map to that observed in the dawn plasma sheet. The total plasma density in both regions was found to be on the order of ~0.01 cm^{-3}, indicating that dawn plasma sheet particles are still present on the dayside but are simply tied to more dipolar field lines. Significant particle densities maintained on the dayside likely enabled the compressive turbulence noted in observations of the cushion region. In addition, localized plasma density enhancements in dayside cushion (e.g., magnetic nulls) may nonetheless arise due to plasma bubble detachment from the outer edge of the magnetodisc current sheet (Kivelson & Southwood, 2005).

The formation of the cushion region postdawn has implications for the mass and magnetic flux transport at Jupiter. The absence of dipolarized flux tubes along the dawn terminator suggests that large-scale plasmoid-based transport, that is, magnetic reconnection along a localized dominant X line (Vasyliunas, 1983; Vogt et al., 2014) may not be the dominant source of mass loss. However, significant mass loss may take place between dusk and dawn local times through mass *drizzle*, that is, gradual diffusive mass loss down Jupiter's magnetotail over a larger area (Bagenal, 2007; Bagenal & Delamere, 2011; Kivelson & Southwood, 2005). Although thick (~1 R_J) magnetopause boundary layers can form during times of significant magnetospheric compressions (Gershman et al., 2017), a systematic magnetosphere-magnetosheath interaction region with the extent of ~10 R_J (e.g., Delamere & Bagenal, 2010) was not observed, suggesting limited solar wind entry into the magnetosphere by viscous interaction along the dawn flank.

4. Conclusions

Through analysis of Juno data, we have demonstrated the absence of a systematic cushion region along Jupiter's dawn terminator. The magnetodisc current sheet persisted beyond distances of 100 R_J, with modest distortions observed only close to the magnetopause. We suggest that the dayside cushion forms as the stretched magnetodisc fields are quasi-adiabatically dipolarized as they rotate toward the compressed sub-solar magnetopause. The absence of a dawn cushion region supports the concept that mass balance in Jupiter's magnetosphere occurs gradually across the nightside magnetotail.

Acknowledgments
All Juno and Galileo data presented here are publicly available from NASA's Planetary Data System as part of the JNO-J-3-FGM-CAL-V1.0 and JNO-E/J/SS-WAV-3-CDR-SRVFULL-V1.0 data sets for the Juno MAG and Waves instruments, respectively. Galileo data are available from the GO-J-MAG-3-RDR-MAGSPHERIC-SURVEY-V1.0 and GO-J-PWS-4-SUMM-SA60S-V1.0 archives for the magnetometer and plasma wave instruments, respectively. This work was supported by the Juno mission.

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